Title
DC Power Distribution in Buildings

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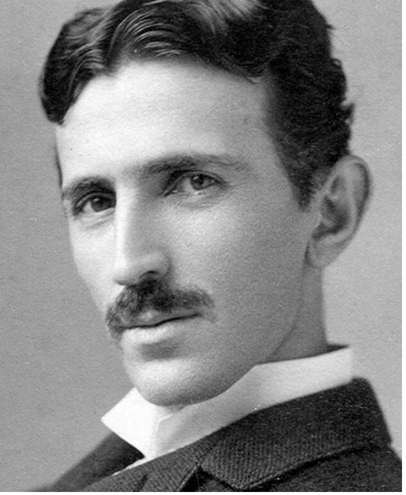
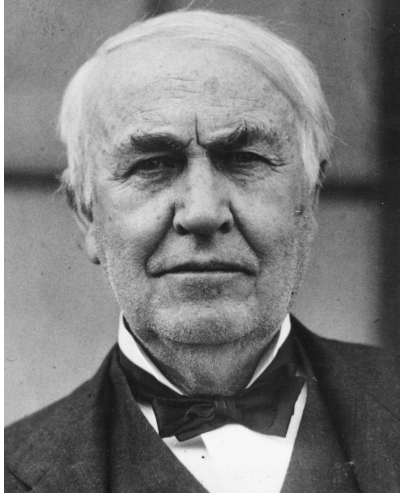


DC Power Distribution in Buildings



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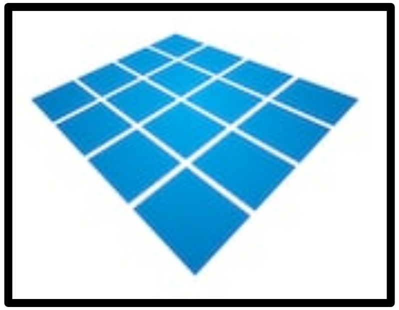
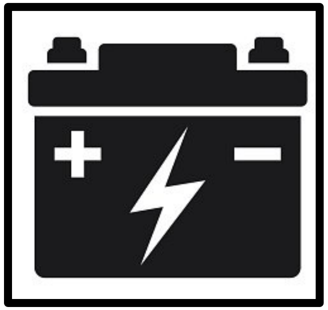
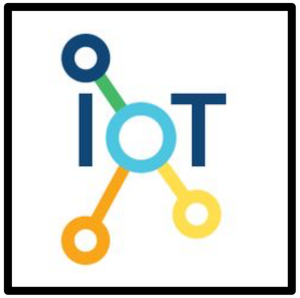
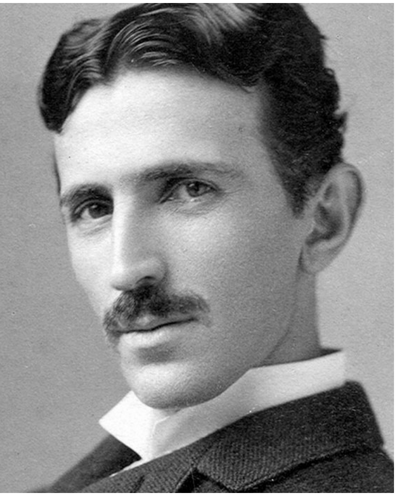


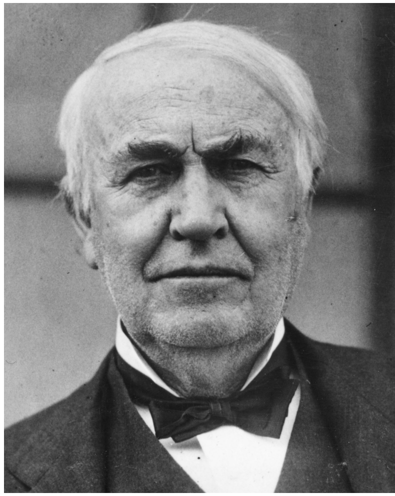






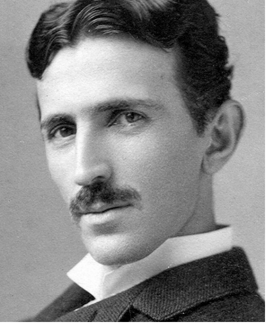
Tesla

War of the Currents: Why We Chose AC



Edison

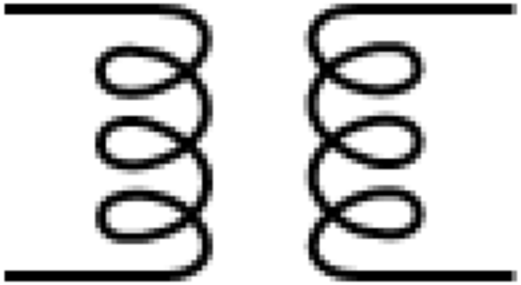
- Back then, AC made sense
  - Transformers require AC
  - AC generation: coal, nuclear, gas
  - AC loads: fixed speed motors, incandescent lamp, resistive heating

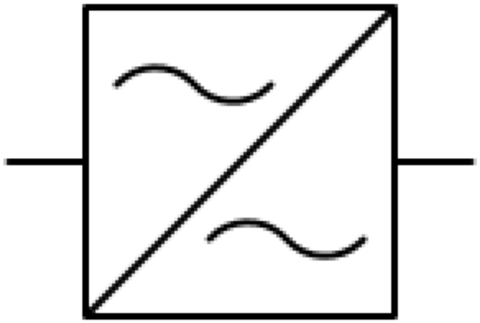


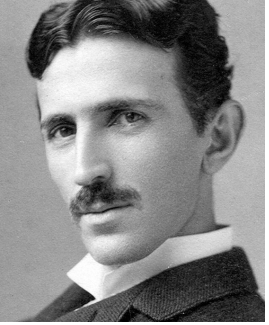
Tesla

Why We Chose AC
Transformers require AC

- Long-distance power distribution requires high voltage to overcome I^2R wire loss
- In the 1880s, voltage conversion required transformers



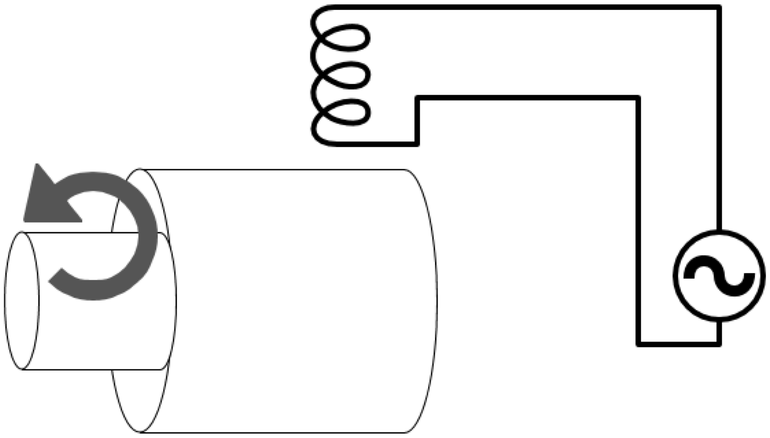


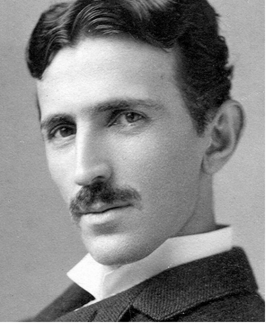


Tesla

Why We Chose AC
AC Generation

- Coal, nuclear, and natural gas plants contain turbines connected rotating equipment
- Induces current in stator (or rotor) coils
- Rotor (or stator) is locked to centralized grid at 60 Hz





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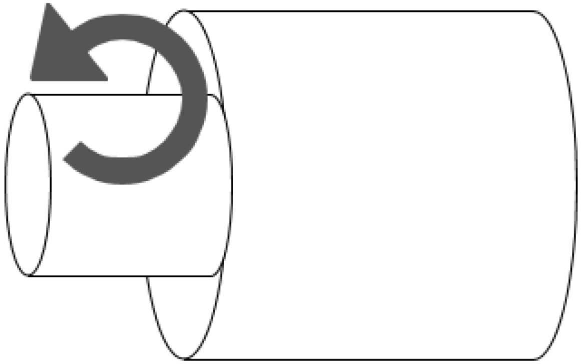
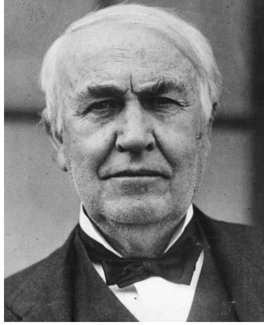
Why We Chose AC
Traditional AC Loads

- Traditional loads interface well with AC
- Incandescent lights
- Resistive electric heating
- Fixed speed motor loads such as compressors, fans, machinery

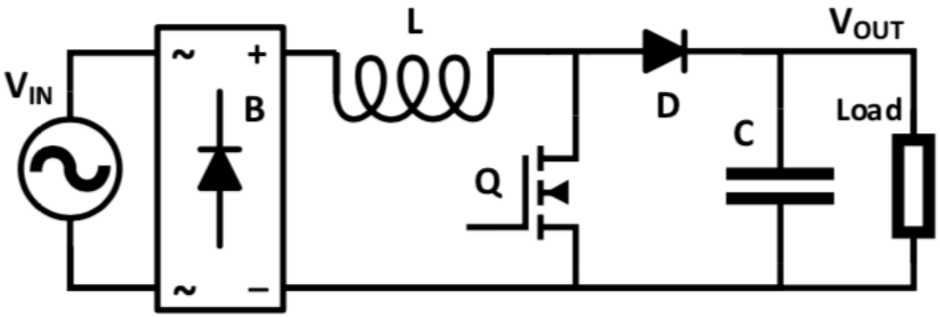


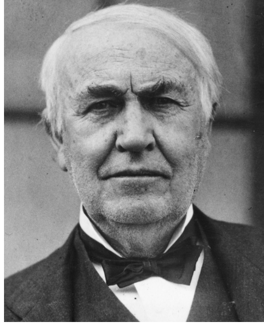
Why DC Distribution?
Power Electronics



Edison

- Allows for DC conversion
- Often more economical than 60 Hz transformer
- Allows precise current control





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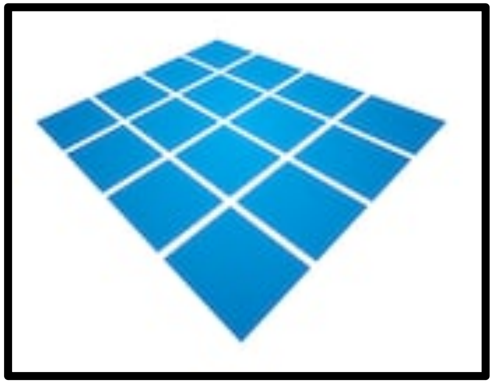
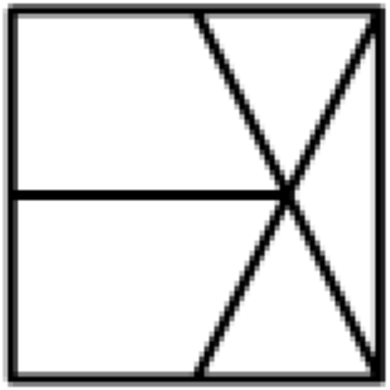
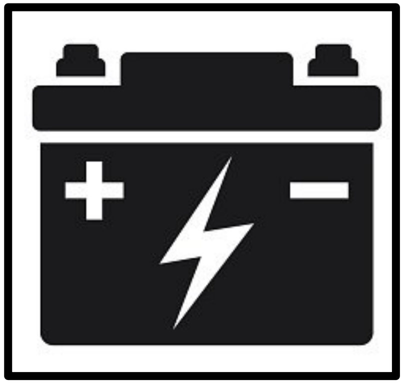
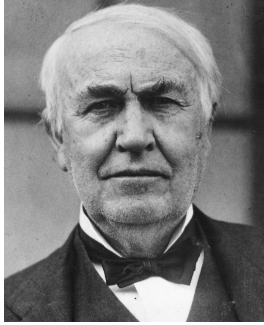
Why DC Distribution?
DC Generation

- Renewable Generation: solar and wind are natively DC
- Electrical storage: batteries are natively DC
- Reduces DC/AC conversions in buildings with onsite generation and storage









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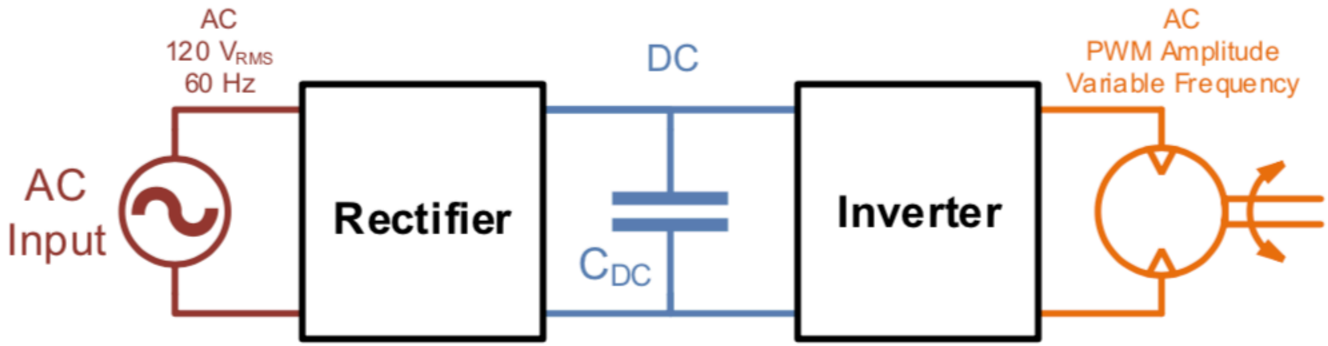
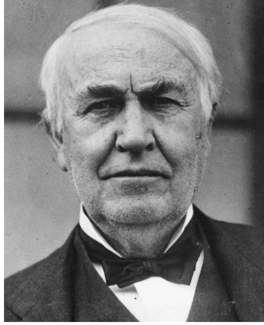
Why DC Distribution?
DC Loads

- Modern loads are internally DC
  - LEDs lighting
  - Electronics
  - EV charging
  - Variable speed BLDC motors in HVAC and water heating
  - Induction stoves
- Many DC power standards: USB, Ethernet





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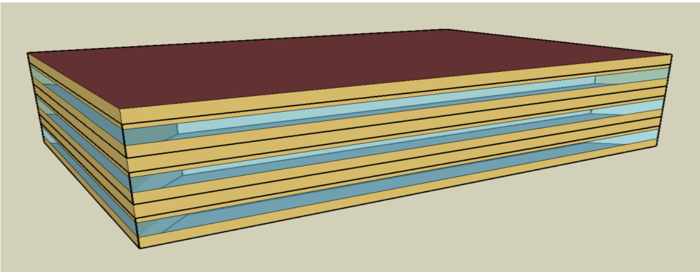
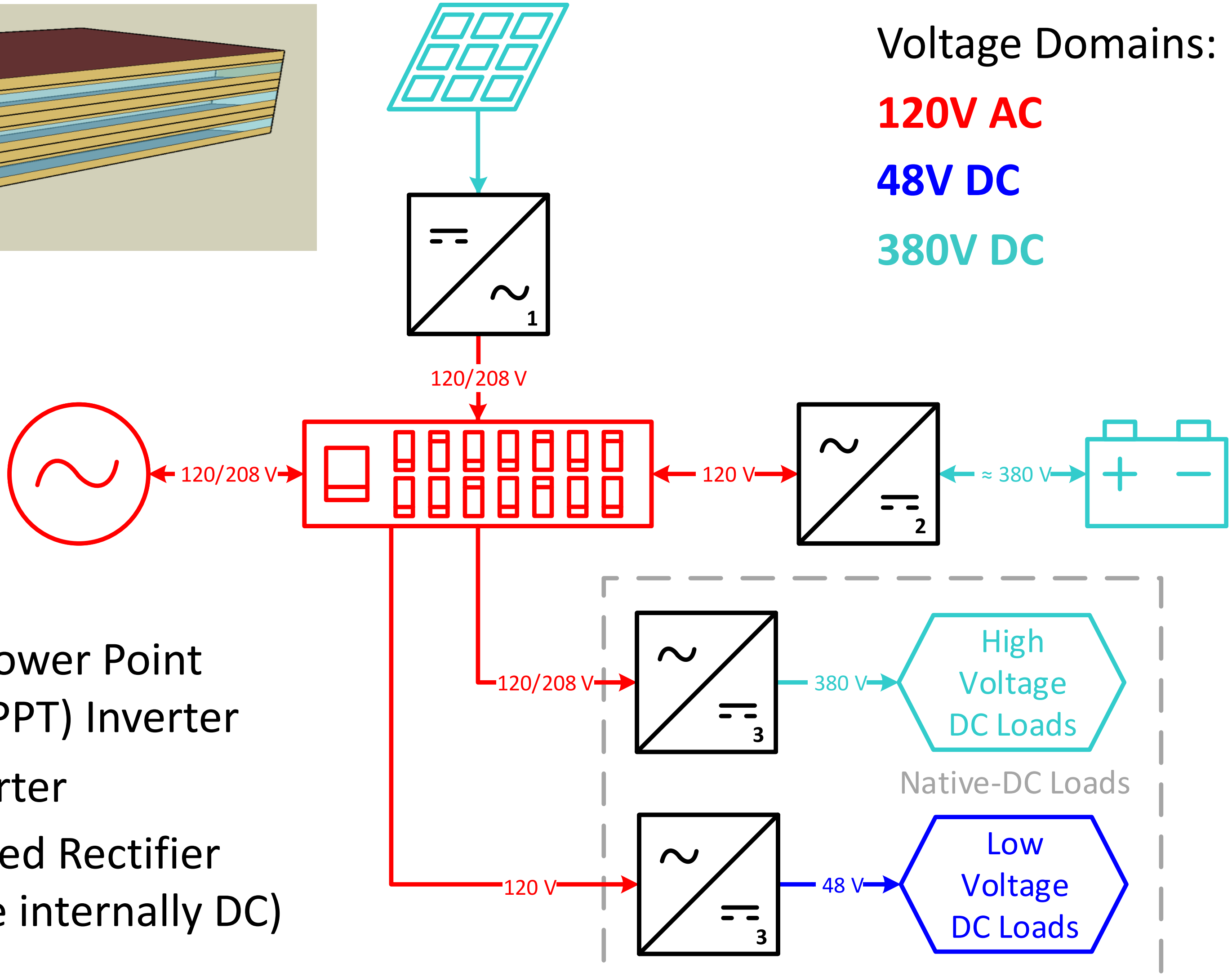
Why DC Distribution? Advantages over AC: Efficiency, Cost, Reliability

- Higher **efficiency** in Zero Net Energy (ZNE) buildings with large solar and storage capacity
- Simple power electronics: better **cost** and **reliability**
- **Reliable** microgrid islanding through power electronics allows for low-cost disaster resiliency
- Improved **power quality**
- **Communications** via combined data and power
- Plug loads **safe** to touch, allows **cost** reduction in wiring

Office Building with AC Distribution





Voltage Domains:

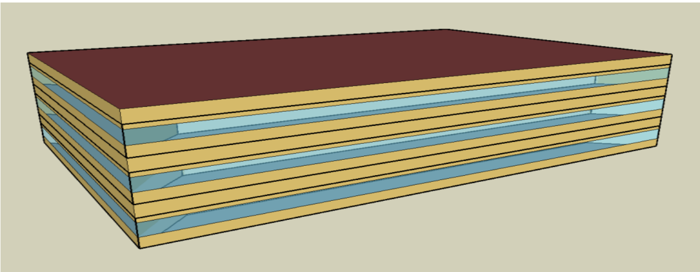
120V AC

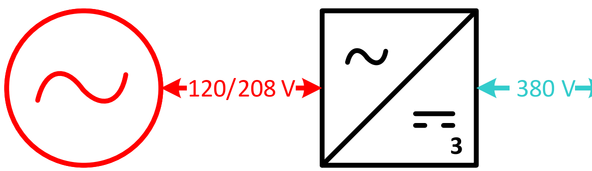
48V DC

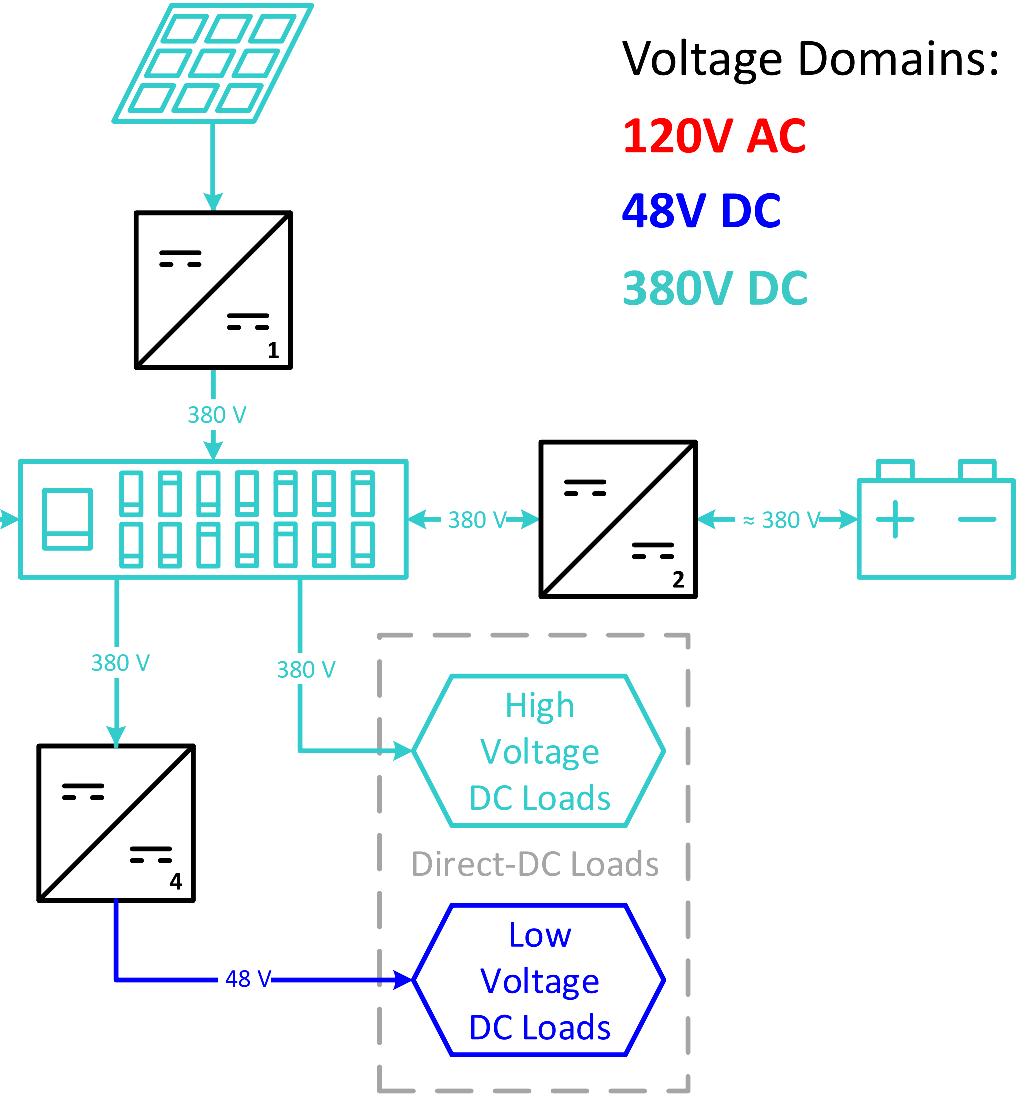
380V DC

1. Maximum Power Point Tracking (MPPT) Inverter
2. Battery Inverter
3. Load Packaged Rectifier (all loads are internally DC)

Office Building with DC Distribution







Voltage Domains:

120V AC

48V DC

380V DC

1. DC MPPT converter
2. DC Charge Controller
3. Grid Tie Inverter
4. DC Distribution Converter

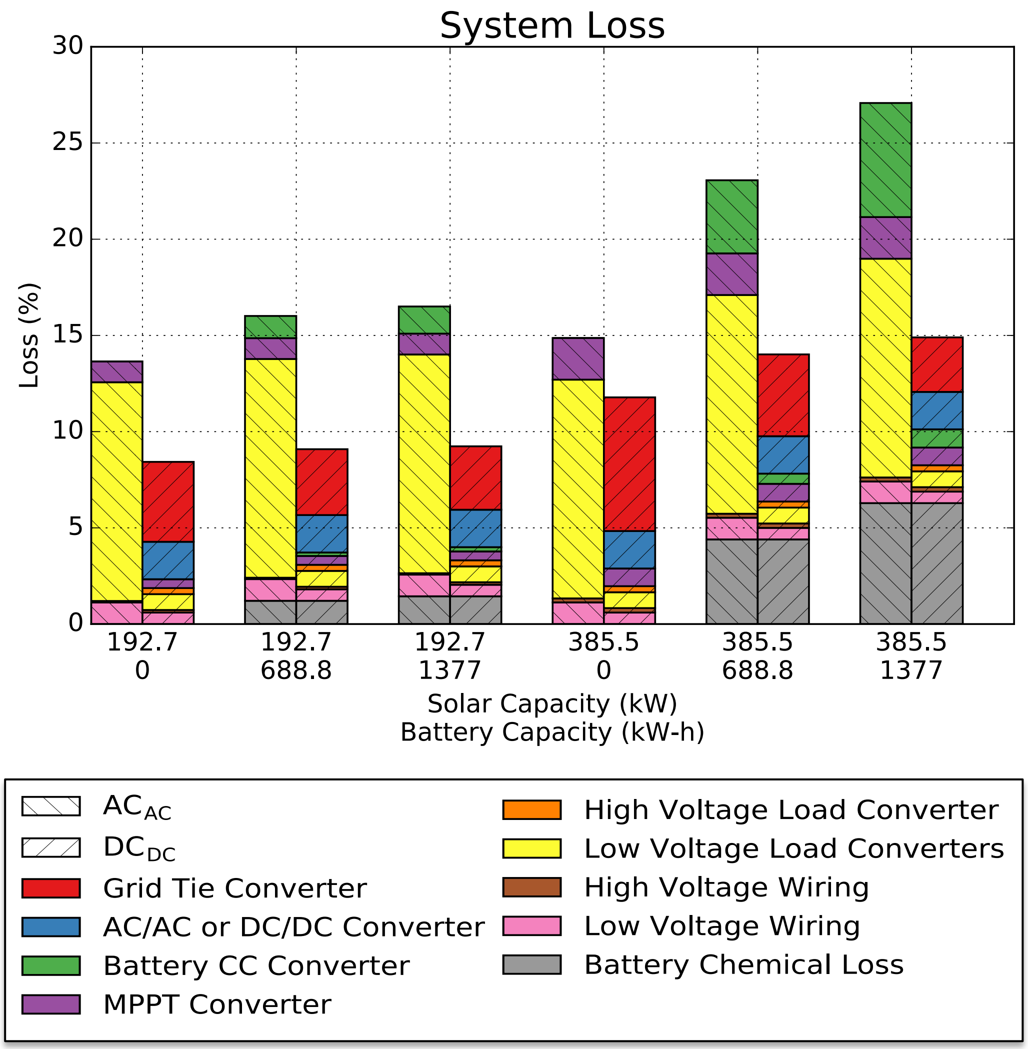
US Department of Energy
Clean Energy Research Center (CERC) Program

Research Goal: Compare AC and DC buildings

- <u>Simulations to determine efficiency savings</u>
- Conduct techno-economic analysis
- Experimental validation

Efficiency Results

- 12% baseline efficiency savings with DC
- Most savings with large solar and battery
- Dominant AC loss: **wall adapters**
- Dominant DC loss: **grid-tie inverter**



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Techno-Economic Analysis

- Results determined from market cost data, grid tariffs, and Monte-Carlo analysis
- First cost is higher for DC
- With significant efficiency savings, the payback period is less than a year

Description	Network	Average LCC Savings (US$)
Total First Cost ($)	AC	252,000
	DC	301,000
Net Annual Electricity Consumption (kWh/yr)	AC	177,000
	DC	101,000
Average LCC Savings ($)	AC vs. DC	61,000
% Cases with Net Benefit	AC vs. DC	>90%
Average Payback Period (yr)	AC vs. DC	~1

$$\text{LCC} = \text{First Cost} + \sum_{y=1}^{\text{Lifetime}} \frac{\text{Operating Cost}(y)}{(1 + \text{Discount Rate})^{y}}$$

$$\text{Payback} = \frac{\text{First Cost}_{\text{DC System}} - \text{First Cost}_{\text{AC System}}}{\text{Operating Cost}_{\text{AC System}} - \text{Operating Cost}_{\text{DC System}}}$$

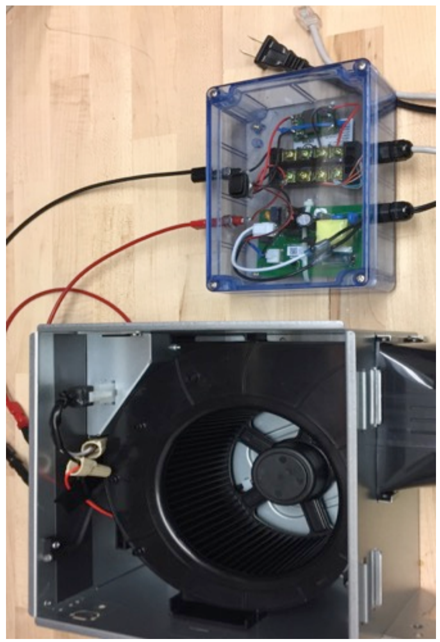
California Energy Commission (CEC)
Direct DC Plug Loads for ZNE Buildings

FUNDING PROVIDED BY THE
CALIFORNIA ENERGY COMMISSION

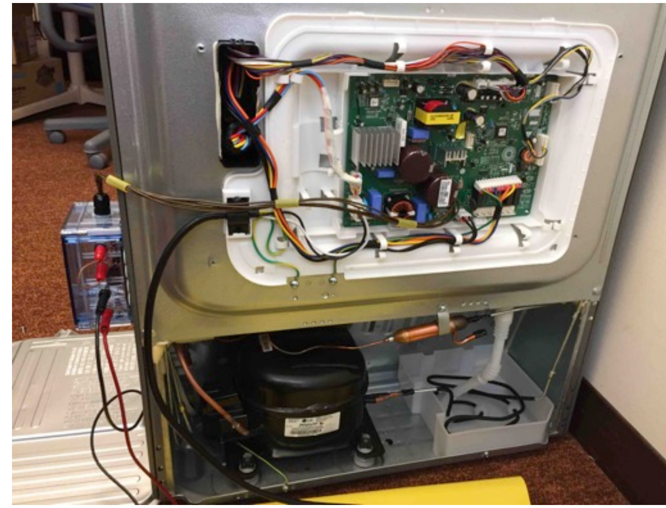
Research Goals

- Modify AC plug loads for direct-DC input
- Demonstrate savings in consumption and cost

Task Lamp
15 V USB-C
~5% W saved



Bath Fan
48 V PoE
8-15% W saved



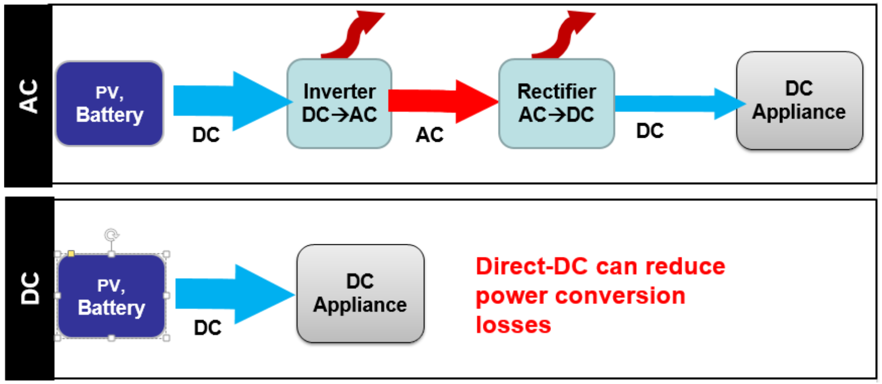
Refrigerator, 380 V DC, 1% W saved
(since original doesn't have PFC)

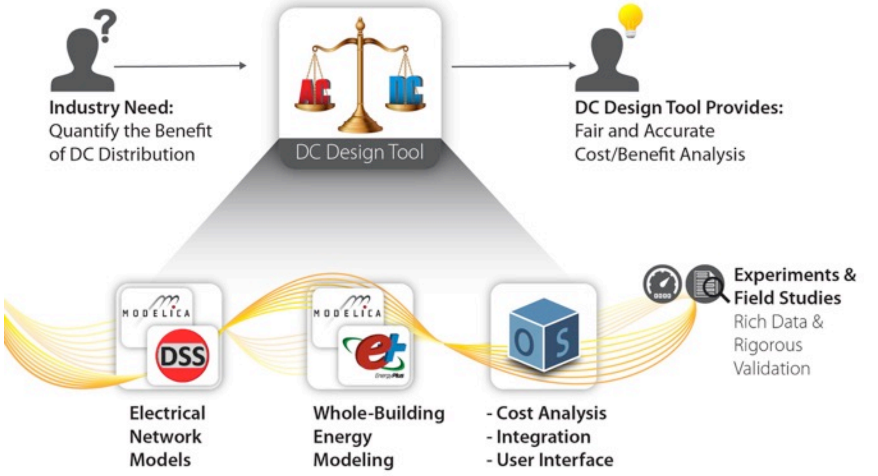
Zone Light, 380 V DC, 6% W saved

NREL/LBNL
DC Design Tool

Research Goals

- Develop an Energy Design and Scoping Tool for DC systems
- Target audience: building planners, designers, and engineers who are considering deployment of DC distribution systems
- Extends DOE's tools: EnergyPlus and the OpenStudio
- Enable user to assess and compare the energy efficiency and life-cycle cost of a design
- Validate the DC Design Tool using collected experimental and field data





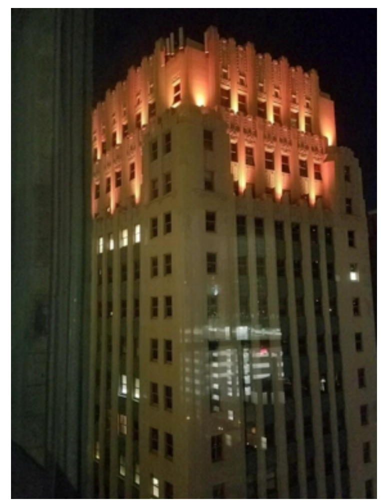
NREL/LBL
DC Field Testing

Research Goals

- Establish evaluation methods and metrics for DC-systems
- Measure and evaluate the performance of several buildings with new DC distribution installations
- Assess technical barriers inhibiting robust adoption of DC systems
- Identify opportunities to optimize DC-system performance

Xingye Solar
Shenzhen

IBEW Building
San Leandro

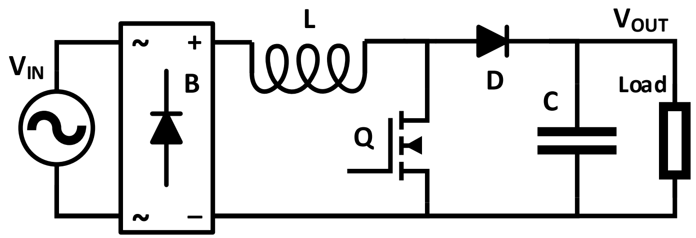


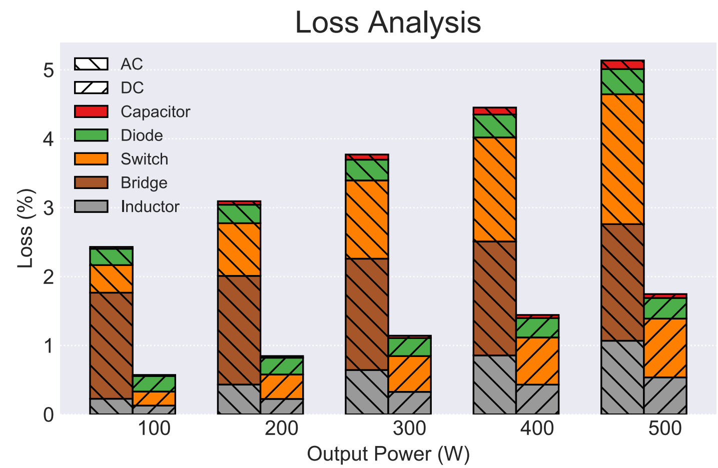
Marriott Sinclair
Fort Worth

IBR Building
Shenzhen

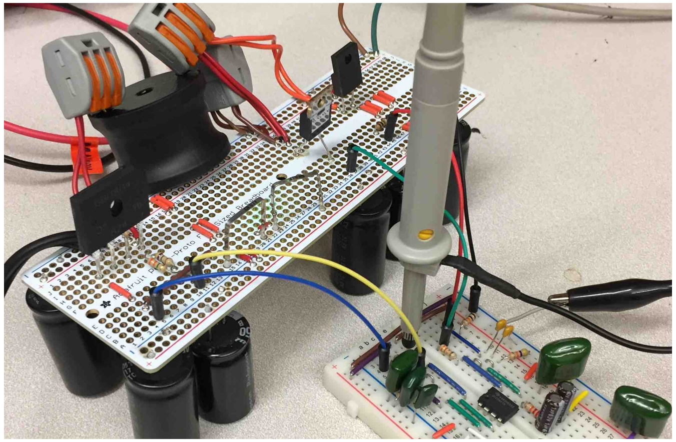
Converter AC vs DC Loss Analysis

- Gaps in Prior Research
  - Converter efficiency based on product data
  - Hard to compare AC and DC
    - Requires a lot of data, which is often unavailable
    - Comparing different voltage levels, eg. 120 V AC to 48 V DC
    - Different components with different parasitics





- Project Goal
  - Develop a detailed boost converter loss model
  - Compare AC and DC boost converter with the same voltage and same components



Non-technical Barriers to Adoption of DC Power

- Lack of DC loads, due to lack of DC buildings
  - Chicken and egg problem
- Lack of standards in voltage and connectors
  - IEC is working on this
- Designers and electricians don’t understand DC
  - Incorrect safety concerns
  - Optimal design for cost and efficiency

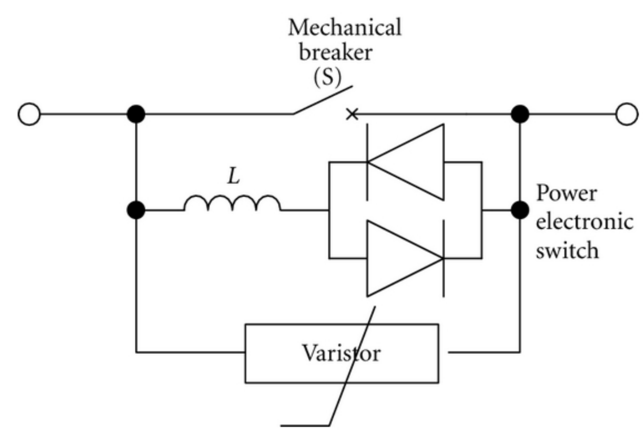
Areas for Further Technical Research in DC Power

- Protection and fault interruption
  - Solid-state, hybrid, converter blocking
- Topology
  - Pulsed
  - Bipolar
  - SST
- Control and stability
  - Current sharing (primary, secondary)
  - Communications, demand response (tertiary)

Protection and Fault Interruption

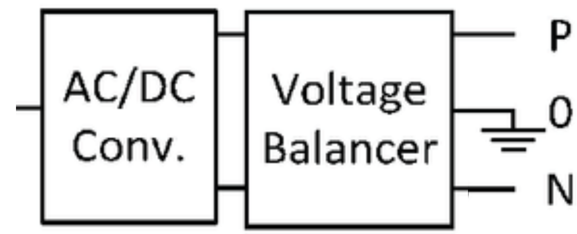
- Problems with mechanical breakers for DC
  - No zero-crossing to extinguish arcs
  - Mechanical breakers too slow, need < 1 ms

- Possible solutions
  - Solid-state breakers - use MOSFET etc. to block
    - Very fast interruption, but on-resistance losses
  - Hybrid breakers – parallel solid-state and mechanical
    - Low on-resistance but slightly slower (~1 ms)
  - Converter blocking – use DC/DC converters as protection
    - Free functionality
  - Most solutions are more expensive than AC breakers
  - Still require series mechanical disconnect

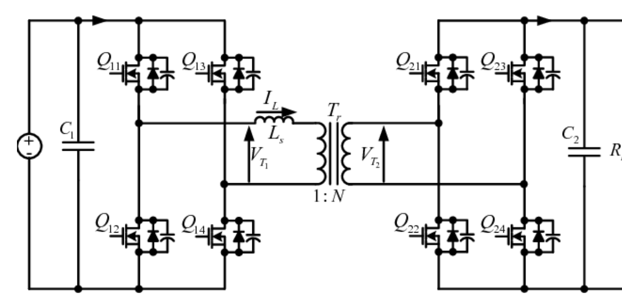


Topology

- Pulsed - Voltserver
  - Pulsing power allows high voltage distribution without conduit
  - Only transfer power after digital handshake
- Bipolar Distribution (+/0/-)
  - Increase power transfer capacity; thinner wiring
  - Pole-neutral loads are resilient to faults on the opposite pole



- SST in Buildings
  - Multiport coupling of solar, storage, grid
  - Isolation between circuits; required for behind-the-meter transactive power



Bus Stability and Control

- Current sharing
  - Primary control – decentralized
    - Often uses droop control to regulate bus
    - Virtual series resistance: $V_{ref} = 380 - i_{out} * R_{droop}$
  - Secondary control – distributed
    - Units communicate to adjust droop parameters to account for network parasitics
- Optimal control for economics or energy
  - Tertiary control – centralized
    - Demand response
    - Price-based control
    - Grid services

Thank you!

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